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Real-time Radiography for CDI Castings X-ray Inspection System

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1. Summary

The purpose of this project is to demonstrate the feasibility of a low cost, real-time radiographic inspection technique for Cast Ductile Iron (CDI) castings which can provide both standard inspection images and three dimensional positional information of image features. The feasibility of this project was demonstrated by real time radiographic experiments on a smaller object at 150 kV x-ray energy and by tangential x-ray imaging of an actual 5" CDI projectile at 280 kV x-ray energy. The greater sensitivity of the new detector technology introduced in this development project makes it possible to use significantly lower x-ray energy than would normally be required for the inspection of such castings. This is an important achievement because the cost of radiographic inspection equipment and facilities is directly correlated with the x-ray energy level. For data display, a new tangential technique for the collection of radiographic data is combined with a Multi Planer Reconstruction (MPR) image display (first introduced in a recent Omega NSWC SBIR). This is used to show both the standard and three-dimensional inspection information. This combination of enhanced detectors, tangential scanning and data display makes possible an enhanced, cost effective, radiographic inspection system which can identify both the features and their position in three-dimensional space in the dense CDI material.

In the early parts of phase I, many problems were encountered with the 300 kV x-ray system. We lost a high tension cable (150 kV) due to high voltage arcing at the connector. A new cable was purchased from the manufacturer. After the installation of the new cable, it was found that one of the 150 kV diode stacks had also failed because of the arcing in the anode high voltage tank. A new stack was purchased and installed. These problems caused significant difficulties and lost time in carrying out 300 kV experiments with the CDI castings.

To move the project forward while we repaired the x-ray equipment, we designed and fabricated a smaller 3" diameter steel phantom and carried out experiments with our 150 kV x-ray system. A small 0.028" diameter hole was drilled on the side of this steel phantom. Using newly designed single channel high sensitivity detectors, tangential scans of this steel phantom were collected to determine the level of contrast possible using only a 150 kV x-ray system. It was found that an optimum design detector can detect the presence of this small (0.028") hole at a location approximately ¼" deep inside from the surface. At 0.25" depth from the surface of the 3" diameter phantom, the x-ray path length is 1.66", *i.e.*, the x-ray beam must travel through 1.66" of steel to reach the surface of the detector. The 0.028" diameter hole is only 1.7% of this total path length. This requires a very high contrast capability if it is to be achieved with only 150 kV x-ray beam. This experiment proved the ability of the new detector design and the tangential data collect technology to image the hole and to show its depth and position in space with just a simple bread board setup.

In the mean time, we were able to repair our 300 kV x-ray system and to also design and fabricate:

- One 64-channel high sensitivity detector array, using the experience gained from single channel detector experiments with the 150 kV x-ray system. This 64-channel detector array was hand fabricated on a bread board. The data flow to a computer system is controlled by an external trigger to the multiplex logic circuits designed into the detector array. A position encoder on the rotary motion stage provided the required trigger for the data collection from the detector array.

- An experimental tangential scanner was constructed to collect data from the 5" projectile. The scanner provided a linear motion to translate the projectile through the x-ray fan beam and a rotational motion to rotate it in the fan beam at each tangential position. This tangential gantry was fabricated using a UNISTRUT type steel erector set. An inexpensive translate and rotate stage was built for the 5" projectile. The translate stage was fabricated from two steel angle bars and four V groove steel wheels. The linear motion was provided by a low speed DC motor and an ACME screw. The linear speed of the system was set to about 1/4" per minute. The rotary stage was built using a heavy duty lazy Susan as a bearing mechanism and a low speed DC motor. A position encoder was included with the rotary motion. This encoder mechanism provided 1024 encoder pulses for each rotation. The rotation speed of the system was set at about 10 seconds per rotation.

  The 300 kV x-ray tube was mounted on one side of the motion stage and the detector array on the other side to collect tangential data from the 5" CDI projectile. The detector was mounted vertically and beam collimation was added to form a vertical fan beam of x-rays between the x-ray source and the detector. The projectile stands vertically on the motion stage so that each detector in the array sees the same tangent in the part at a slightly different vertical position. The part is rotated and slowly moved through the fan beam during data collection.

- Preliminary data collection and display software was written for this test set up and many scans of the projectile were collected. The projectile is 5" in diameter with a hole about 1.6" diameter in the center giving a path length of approximately 3.4" of steel through the center. A steel patch (2" x 2" area and 0.035" thick) and a 0.035" diameter steel wire were attached to the outside surface of this 5" projectile as quality indicators. For later scans, 0.024" and 0.050" thick steel MIL STD penetrameters were also added as quality indicators.

Over a period of two months, many tangential data sets were collected for the 5" projectile using this set up. We used our x-ray system at less than 280 kVp because it was showing signs of arcing above this. The patch (2" x 2" area of 0.035" thick steel) can be seen in the entire central region of the data set and the 0.035" diameter wire can be seen in most of the central region of this data set. We know that in the regions of our data, the 5" projectile has a total wall thickness (two walls) of 3.34". The data clearly indicates that our designs can detect contrast of less than 1.25% through 3.4 inches of steel using less than 280 kVp x-rays.

The experimental work of phase I clearly indicates the feasibility of the technique. The greater sensitivity of the new detectors significantly reduced the energy required to image the projectile and the MPR image display provides three-dimensional position information. We were able to achieve a 1% contrast level through 3.4" thickness of steel using x-rays of ≤280 kVp. It is predicted that better than 1% contrast can be achieved for CDI objects with thicknesses of ≥5" thick using the Tangential scanning technique. This conclusion is based on the data from the phase I experiments and the implementation of the following improvements:

(1) The phase I system was used with x-rays of less than 280 kVp. The proposed CDI system will have a 450 kV x-ray system. At 450 kV, there will be much greater penetration through the casting.

(2) Omega's x-ray system (used during phase I) is a 60 Hz system and has about 10% of 120 Hz ripple in the data. This 60 Hz x-ray ripple causes significant noise in the data and

reduces the contrast visibility. The actual CDI system will have a high frequency constant potential x-ray system without any external ripple in the data.

(3) The 64-channel detector array was hand built. A manufactured detector system will offer slightly better performance.

(4) The phase I mechanical system is a bread board system that has very crude and inaccurate motions. The properly designed gantry of the proposed CDI system will provide accurate and vibration free motions. This will lead to better quality data.

(5) Only preliminary data analysis tools were used to view and analyze the phase I data. More advanced analysis tools can resolve smaller features from noisy data if some difference in characteristics of noise and feature can be identified.

The positive results achieved in phase I suggest that the navy should continue this project, fabricating a prototype system in phase II, and a complete production system in phase III.

2. Objectives from Phase 1 Proposal

The objectives outlined in the phase 1 proposal were:

First Major Goal

Phase I Technical Objectives: *We propose that during the initial part of phase I, Omega will develop technical ideas and preliminary designs for the Real-time Radiography (RTR) System for CDI castings. Omega will use its presently owned 60 Hz 300 kV x-ray system and fabricate several different discrete detector channels for experimentation during phase I. We will measure x-ray signal strength, signal-to-noise ratio and x-ray interference signal due to scattering as a function of steel thickness, detector size, detector depth, integration bandwidth and various distances. This will provide us an idea regarding the ultimate performance of the hardware system. These phase I experiments will also provide sufficient information to predict the performance of a RTR system for large CDI castings.*

Second Major Goal

Omega already possesses two 5" diameter CDI castings, but we will try to either acquire few larger size CDI castings with known defects from NSWC or fabricate a few pieces with controlled known defects to collect some of this data.

Third Major Goal

Towards the end of phase I, we will generate preliminary design of a prototype RTR system to be fabricated during the phase II period. The preliminary designs will use the ideas generated during phase I. The phase I preliminary designs will include the overall design concept of the prototype system, its expected performance, and specifications of various subsystems required. The phase I designs will not provide detailed and complete set of drawings and specifications but only preliminary design.

The detailed designs of the prototype system and its fabrication will be completed during phase II. The phase III will provide designs of an automated RTR inspection system for production application.

3. Achievements of the Phase 1 Research

We met all of the proposed objectives of the phase I proposal as well as accomplishing a number of other tasks. Specifically:

- When our 300 kV x-ray system had broken down for several months, we constructed a small tangential gantry system with four computer controlled motions and collected tangential data on a 3" diameter steel phantom with several single channel detectors using our 150 kV x-ray system. This small tangential scanning system and the experiments performed on it, provided significant information about the design and performance required for the optimum detector system for CDI castings.

First Major Goal Completed

- After repairing the x-ray system, we designed and fabricated a full size experimental tangential test scanner to collect data from a real 5" CDI projectile. We also designed and fabricated a prototype 64-channel solid state detector array using most of the design parameters determined to be optimum from the single channel detector used in the small tangential system (see above). We collected several tangential scans of the 5" projectile using the 64-channel detector and 300 kV x-ray system. This system was fabricated to investigate the likely problems and actual usefulness of a tangential scanning system for CDI castings.

Second Major Goal Completed

- We wrote software for data collection, display and analysis. We investigated several different software techniques to automate the identification and analysis of flaws in the data from the CDI castings we had scanned. In addition to the 5" CDI projectiles, we also scanned a wide range of other objects with the test system. The raw data from this test system and the investigated analysis techniques all indicate that it should be possible to develop a system that will automatically detect the flaws in the CDI castings and thus meeting the ultimate goals of this research project. The details of the fabricated test system, collected raw data and analysis are included in the later sections of this report.

- We have had numerous visits and discussions over the last several years with the NSWC technical coordinator Mr. Larry Crabtree and Mr. Harry Vivion. Dr. Nand Gupta of Omega has visited NSWC-Dahlgren several times, the last visit taking place on 01/17/97 when we discussed the results of some of the 5" projectile data collected from the tangential gantry. During the course of these discusssions we have established:
  - The navy's functional requirements for a digital tangential radiographic scanner,
  - The performance and limitations of the present techniques using the UT methods,
  - The present techniques in use by the navy and its vendors,
  - The typical sizes and structure of the CDI castings.

- For this preliminary digital tangential scanning system design, we have made extensive computations of:
  - The expected performance (signal-to-noise ratio) of the detected signal,
  - The system performance of the assembled digital tangential scanner system for largest CDI castings.

  The computations are made for cracks, voids and inclusions of various sizes in the steel castings of various thickness. These computations show that, with the use of the low

noise detector array we can obtain, at lower kV, a better contrast resolution without sacrificing the spatial resolution.

Third Major Goal Completed

- We have evaluated several detector materials, investigated x-ray system types, x-ray technique and mechanical gantry performance. Based on these investigations, we have generated a preliminary system design of a optimum digital tangential scanning system suitable for the navy's application. This prototype would be fabricated during the phase II period – see Section 5 of this report.
- This final report is submitted to NSWC describing most of the technical work performed during phase I.

4. Technical Work Performed in Phase 1

4.1 Experiments with Single Channel Detector and 150 kV x-ray System

During first three or four months of this phase I contract, our 300 kV x-ray system had several unexpected problems with arcing in the high voltage cable and later failure of the high voltage rectifier stack inside the high voltage tank. These problems had made our 300 kV x-ray system inoperable for several months.

To overcome this difficulty and keep the overall schedule of the phase I research during this period, we designed and fabricated a small tangential scanning gantry capable of scanning a 3" diameter object.

This small tangential scan gantry consists of following four axes motions under computer control:

- 24" x- axis motion (stage A),
- 2" x- axis motion (stage B),
- 2" y-axis motion (stage C),
- 360° θ motion with rotary axis parallel to y-axis (stage D).

The rotary motion stage (stage D) is mounted on the top of the y-axis motion stage (stage C), which in turn is mounted on the top of 2" x-axis stage (stage B). All this combination of three motion stages is mounted on top of the 24" x-axis motion stage (stage A).

One single channel x-ray detector (pointing upwards) was mounted on the 24" x-axis (stage A) motion stage. A narrow lead collimator (0.01" diameter) was included on top of the detector to reduce the scatter radiation in the detector.

The 150 kV x-ray tube was mounted vertically above the entire tangential gantry with the x-ray beam pointing vertically downwards. A slit collimator was mounted at the x-ray port of the x-ray tube to limit the x-ray beam in a narrow fan parallel to the y-axis. An overall picture of this set up shown in figure 1. Figure 2 shows a closer view of the set up with the test sample on the motion stages, the detector and the x-ray tube.

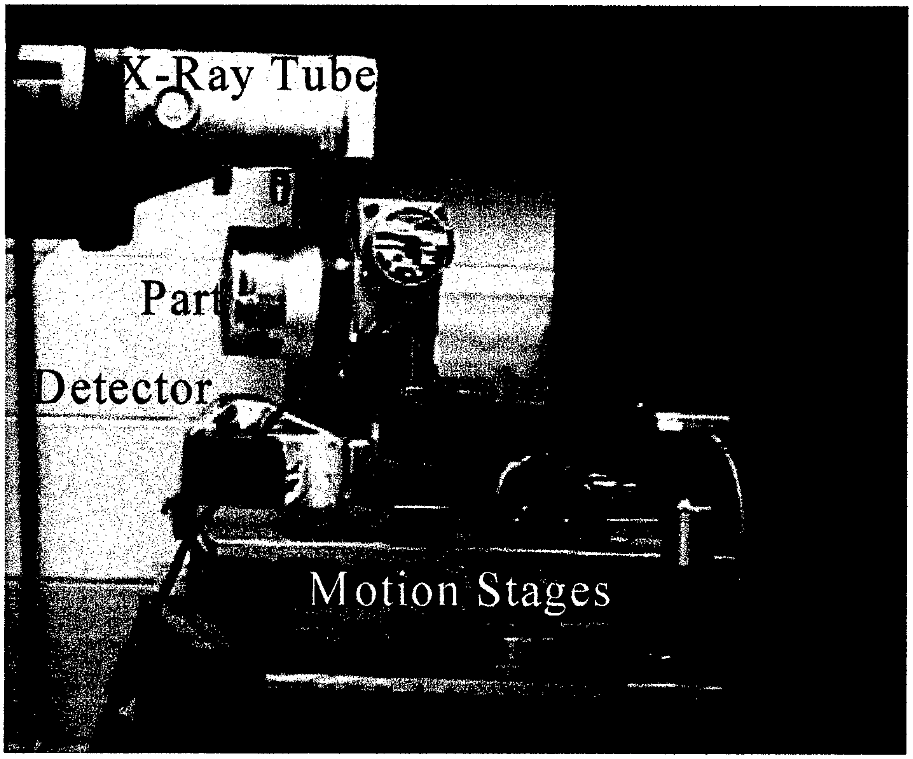

Figure 1: General View, 150kV Scanner.

The narrow collimator of the single channel detector was aligned to the fan shaped x-ray beam by the stage A. As the detector was traversed along the x-axis using stage A, the detector detects maximum x-ray signal when it is aligned to the beam. After the detector alignment, the power to stage A was permanently disconnected to avoid accidental misalignment of the detector.

A 3" diameter cylindrical steel phantom was fabricated for experiments with this system. A 0.028" diameter deep (>0.25" deep) hole was drilled through the side of this cylinder. One 0.029" diameter steel ball was also attached to the surface of this phantom near this hole. This phantom was mounted on the rotary stage such that the axis of the steel phantom is parallel to the y-axis.

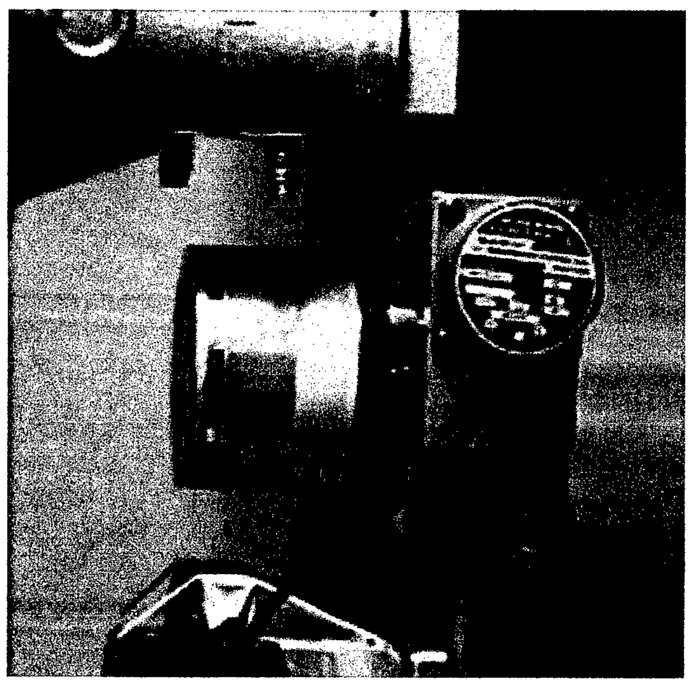

Figure 2: Close-up of 150 kV Scanner.

With the x and y motion stages (stages B and C), the steel phantom was aligned to the x-ray beam such that the 0.028" hole just hugs the x-ray beam. In other word, the y- coordinates of x-ray tube focal spot, the detector collimator and the hole of steel phantom are identical. Once, the y coordinate of the hole in the steel phantom were aligned with the x-ray beam, the power to the y-axis (stage C) motor was permanently disconnected to avoid accidental misalignment of the phantom. Now we were ready to collect tangential scans of this phantom with small hole.

To collect the tangential scan, this steel phantom was continuously rotated and translated along x-axis (stage B) under computer control. The phantom was translated by 0.005" after each rotation. 3000 data points were collected during each rotation of this phantom.

A complete tangential data set consists of 50 rotation of the phantom as it traversed a total distance of 0.25". At the end of this traverse, the x-ray beam must travel through a 0.25" deep path from the outside surface. For a 3" diameter circular object, this path length through which the x-ray beam must travel is 1.66". Several such tangential data sets were collected with several different single channel detectors.

These tangential data sets were organized for display and analysis. As the detector designs were optimized, it became possible to find the 0.028" diameter hole even at a depth of 0.25" i.e. through 1.66" path length. We realize that the average energy of the x-ray beam for a 150 kV x-ray system is probably < 100 keV. At 100 keV, the linear attenuation coefficient for iron is about 2.86 cm^{-1}. Hence, only 5.6 x 10^{-6} fraction of the x-ray intensity can reach the detector after passing through the 1.66" path in the steel phantom. Being able to see the 0.028" diameter hole in this data set shows the phenomenal capabilities of the tangential data collection technique and this detector design.

An image of one of such tangential data set display is shown in figure 3. In the top half image in this figure the dark parabolic curve in the left side of the image shows the signal due to one of the steel balls on the surface of the phantom. A light shade parabolic region in the middle is due to the 0.028" hole at the surface of the steel phantom. The second dark parabola (in the right side of the image) is due to the second steel ball on the surface of the phantom. The part of the signal due to the second ball is lost due to a unique software problem for the rotary motion system. The bottom half of the figure 3 shows a x-axis line profile through the blue line in the upper half image. In the x-line profile, the signal through the steel balls and the hole are very clear. Each steel ball shows two dips in the signal, while the hole shows an increase of signal in the region. Since the hole has finite (large) depth, the signal due to the hole covers an entire region.

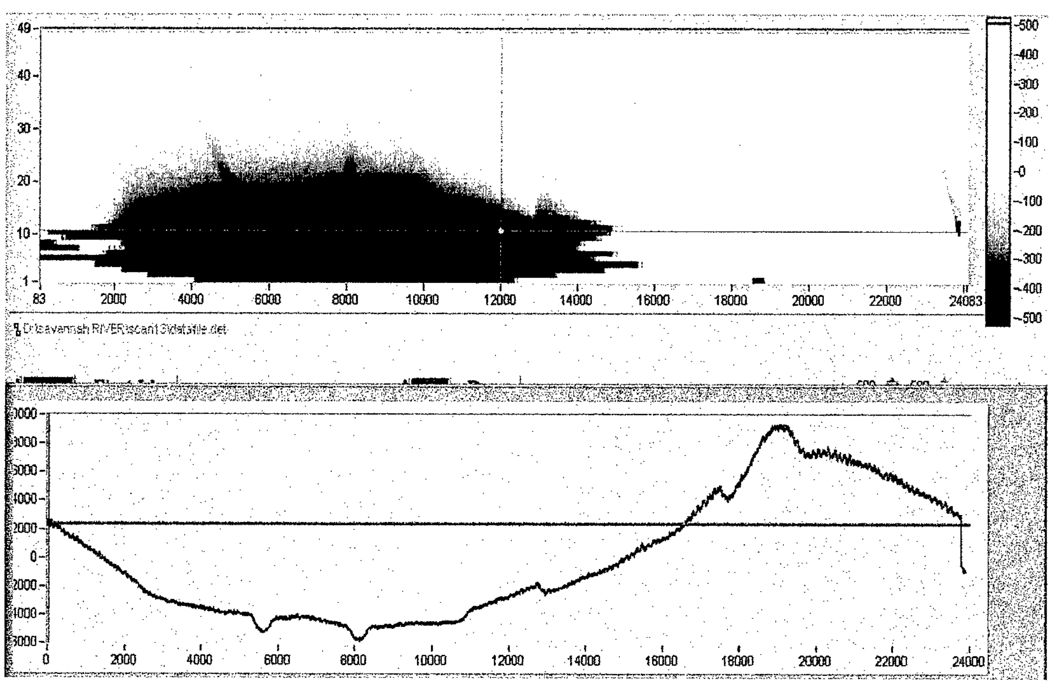

Figure 3: Data from Scan of 150kV Phantom.

4.2 Experiments with Full Size Tangential Test Set Up

Once the 300 kV x-ray system was repaired, we designed and fabricated a full size experimental set up to collect data with a real 5" CDI casting. This included a gantry, a 64-channel detector array and software.

The Gantry

This tangential gantry (see Figures 4 and 5) was fabricated using a steel erector set type structure made by UNISTRUT corporation. Essentially, a large frame was bolted together using 2" and 2.25" square cross section UNISTRUT tubing. The UNISTRUT tubing has 3/8" diameter holes at 1" regular spacing on all four sides. This offers a method to construct a custom frame of any reasonable size in a short period. Thus constructed frame is not as accurate and rigid as properly machined and welded structure, but it is an inexpensive and quick method to construct frames for experiments. After construction, this experimental gantry was moved inside our 16' shielded room for data collection with 5" projectile.

The 300 kV x-ray tube was mounted on one side of this frame and the detector array on the other side. The x-ray tube and the detector array were mounted about 24" above the ground level. Except for a narrow (1/8" wide) slit opening for primary radiation beam, the x-ray tube head was surrounded by at least 4" thick lead shielding to reduce x-ray radiation in the surrounding area. This shielding not only reduced the general radiation level in the surrounding area but also eliminated the production of most of the scatter (unwanted stray) radiation in the general area. Such scatter is a source of problems in any x-ray imaging system. The quality of the data suffers significantly due to scatter radiation in most x-ray imaging systems. Except for a narrow (1/8" wide) slit for primary x-ray beam entrance, the detector array was also surrounded by at least 2" thick lead shielding. This shielding around the detector array reduced or almost eliminated all of the scatter radiation from entering the detector array. The x-ray tube source and the detector array collimators formed an x-ray fan beam traveling in a horizontal direction. The axes of the source and detector slits were in the vertical direction and were precisely aligned to each other by a laser beam.

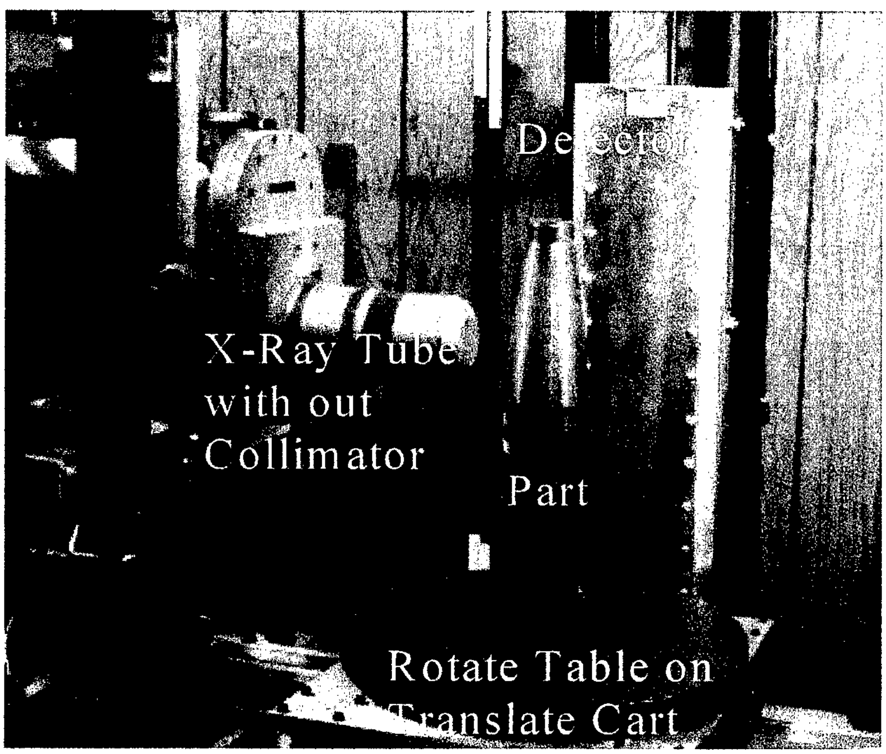

Figure 4: Experimental Scanner.

Between the x-ray tube and detector array, a translate and rotate stage was built for the 5" projectile. The translate stage traveled horizontally, perpendicular to the plane of the x-ray beam. The rotate stage provided a continuous rotation with its axis of rotation in vertical direction.

The linear motion of the translate stage was achieved with two steel angle bars and four V grooved steel wheels. The two angle bars were mounted parallel to each other to provide tracks for the translate stage. A rigid trolley was fabricated from 1" thick aluminum plate and the four V grooved wheels. This trolley traveled along the tracks. This provided a low friction linear motion mechanism to traverse the projectile. A 1" diameter ACME screw and a low speed DC motor provided the linear motion to this trolley.

The rotary stage of the trolley was built using a heavy duty lazy Susan bearing mechanism and a low speed DC motor. The bearing was mounted on the top of 1" aluminum plate to allow rotary motion between surfaces. A 2" thick wood disk was mounted on the top of this lazy Susan. This wood disk was used as the base or mount for 5" projectiles. The wood disk was driven by a low speed DC motor through a heavy duty chain and sprocket arrangement. A position encoder was included with the rotary motion. This encoder mechanism provided 1024 encoder pulses for each rotation. Figures 4 and figure 5 are pictures of the experimental system with a 5" projectile in place.

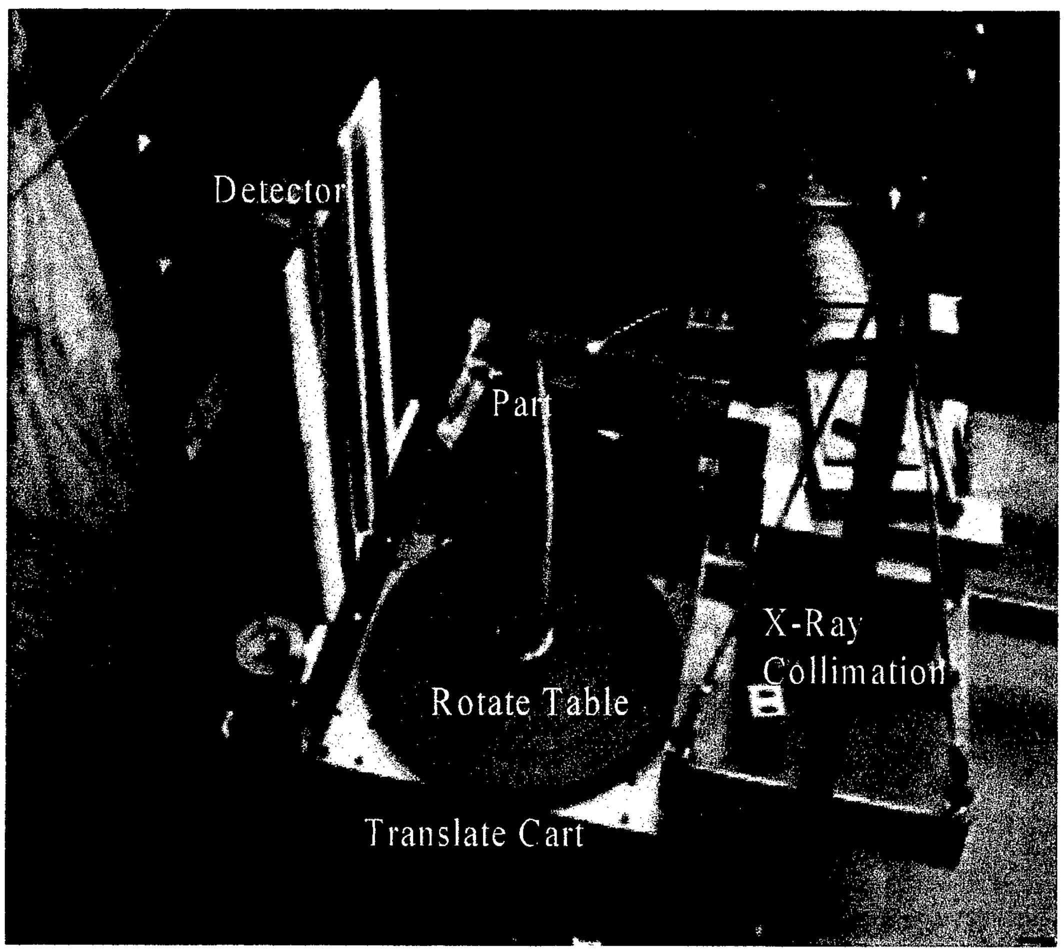

Figure 5: Experimental Scanner.

In a typical application, the projectile was continually rotated with a rotation speed of about 10 seconds per rotation. The linear speed of the system was set to about 1/4" per minute. Neither the translate or rotate speeds were perfect. There were significant (short and long term) variations in these speeds. This allowed us to collect 1024 x-ray angular views per rotation and 24 rays per inch through the object during a typical tangential scan. A typical tangential scan with 6" translation of the projectile through the x-ray beam produced about 20 Mbyte long data files. Some other larger data sets were also collected with slower motion of the translate stage which generated more rays per inch. Larger data sets have slightly better noise performance, but they became harder to display and analyze on our computer system with only limited 64 Mbyte of memory. Better computer with more memory will easily solve this problem.

The errors in the rotation speed were easily overcame by the encoder system. The 64-channel detector system included logic circuits to collect data when triggered with an external pulse. The position encoder on the rotary motion stage was used to provide the trigger, thus synchronizing the data collection to the angular orientation of the casting, independent of any variations in the rotation speed. The small problems due to speed errors in translate stage were ignored.

The Detector Array

A 64-channel detector array was hand fabricated by modifying one of our pipe scanning (ThruVU) detector array. These detectors represent a breakthrough in sensitive response to low levels of radiation. The pipe scanning application requires very sensitive detectors because of the low flux level from isotopes. This experience was used as a base to develop the detector for the x-ray inspection of CDI projectiles. Omega's ThruVU scanning system uses a ^{192}Ir radioactive isotope as a source of radiation to measure corrosion/erosion in insulated pipelines in oil and chemical refineries. One of the ThruVU detector arrays was modified to work with the 300 kV x-ray tube source. The individual detector channel circuits were modified to include the knowledge and experience from experiments with single channel detector system. Mainly, the $CdWO_4$ scintillator depth was set to 6 mm for efficient detection of 300 kV radiation without much contribution from stray radiation. And bandwidth of the detector system was set to about 30 milliseconds to limit the electronic noise.

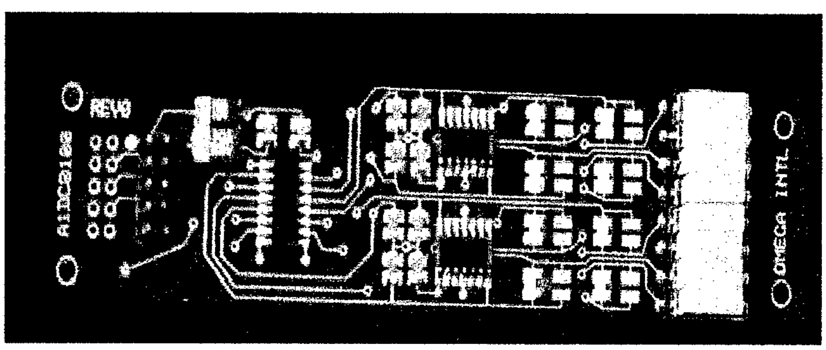

Figure 6: Detector Module.

The detectors are modular in construction. Figure 6 at the right is an eight element module used in the construction of larger arrays. The vertical white strip at the right of the PC Board is the array of crystal scintillators. They are individual elements with a septa or separation to reduce cross talk. Each crystal is bonded to a separate photo diode. The detectors work by capturing x-ray photons in the scintillator which converts them to light. The photo diode for that scintillator responds to the light with an electrical output signal level correlated to the photons captured. The signal from the photo diode is then amplified and multiplexed for transmission to the data collect computer system. High sensitivity is obtained from the

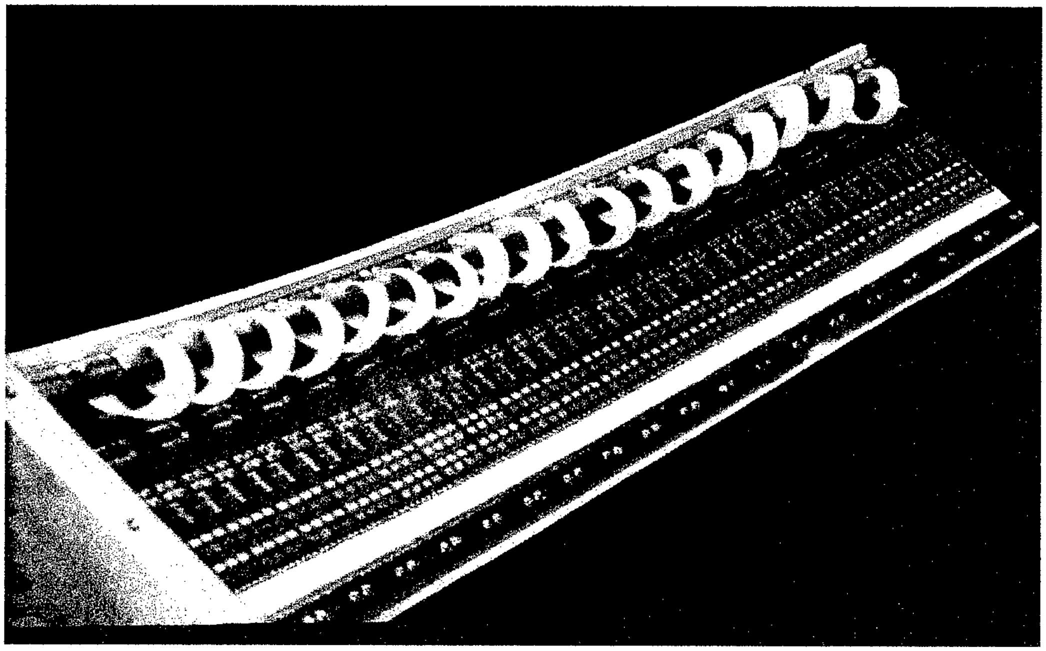

Figure 7: Large Detector Array Manufactured By Omega International Tech..

detector because of the photon capture efficiency of the thick, dense, scintillators and the low noise high gain amplification possible with proprietary design and manufacturing techniques.

The individual detector modules are laid side by side to create a large linear array for industrial applications. Figure 7 shows a whole array of detector modules assembled together. The multiplexed channels are combined together in the enclosure for signal transmission to the data collection computer.

Other Data Collection Hardware

An off-the-shelf PC Computer based 16 bit analog-to-digital convertor board from National Instrument was used to digitize the detector array signal. A 120 MHZ Pentium based PC Computer with 64 Mbyte memory was used to collect, display and analyze the tangential scan data.

The Software

Preliminary software was written to collect data from the experimental system. A second program was written to display the 16 bit three dimensional data. This software was written in National Instrument's LabView environment running under Windows '95. This data display is similar to the 8 bit Multi-planar Reconstruction Display (VIEWMASTER) delivered with the earlier NSWC SBIR system for small rocket motors. The new software has expanded the display and analysis capability to include 16 bit data.

To create the 3-D display of the large tangential data file, the collected data file is reassembled as a block of data. For three independent views, this data block is cut into along three orthogonal axes. Thus displayed, the three views are tangential, radiograph and sinogram. The tangential view is essentially the entire rotation data (360^0 data) at one single radius. The data for all other rotations at various radii are stacked as different pages in a book. If we cut through this book of data along horizontal direction and look at the edge of the pages exposed, we see a traditional radiograph of the object at one rotational position.

If we make other horizontal cuts we expose other similar radiographs of the object at different rotational positions. A vertical cut through the data book exposes a sinogram display of data from one individual detector of the linear detector array. Other similar vertical cuts give us other sinograms at other detector positions. Sinograms are the raw data format from which computed tomography (CT) images are reconstructed. Each and every one of these three views i.e. Tangential, Radiographic and Sinogram individually have all the 3 D information necessary for locating any image feature in three dimensional space. Figure 8 shows the Multi Planer Reconstruction display developed for this project.

Data Collection Routine

The data collection routine is made up of offset, gain and actual scan data collection with the object in place.

OFF SET CORRECTION. The data collection routine allows the operator to first collect the offset of all 64 detectors. For each detector channel, a series of 200 lines of data without any x-rays is collected and averaged to determine the average offset value for each detector channel. This offset value is subtracted from each measured value from every detector before any other calculations are made.

GAIN CORRECTION. For each detector channel, the software routine allows the operator to collect a series of 200 lines of data with x-rays turned on and attenuated by any one of four different thicknesses of any material. Each set of 200 readings for each detector are averaged to determine the average value of signal for that thickness of material. This measures the signal values through four different thicknesses for each detector channel. After these four measurements, the signal values for each detector are fitted to a line to measure the average value of the gain for each detector in the range of thicknesses. This is a method to teach the system how, for each individual detector, to convert a measured signal value into an equivalent thickness (or density) of material. This removes the effects and errors due to detector variations as well as the x-ray beam intensity variations.

Sometimes these gain correction calculations are made using the raw detector readings themselves. If we are dealing with very large thickness variations (as in the case of projectiles), these gain correction calculations are made after taking log of the measured signal. The x-ray intensities are more linear in the log domain and data fits better. After the gain correction, the data looks uniform through a constant thickness object. Any variations in the remaining data represent real density (or thickness) variations of the object.

TANGENT SCAN. The data collection routine is started manually. Once the data collection routine is running, it collects one line of data (64 readings - one from each detector) for each trigger pulse received from the encoder of the rotary motion. The next 64 readings are collect when next trigger pulse arrives from the encoder and so on. The process goes on until either the data collection routine is stopped manually or trigger pulses stop coming. As the data is received by the computer, it makes on-line offset and gain corrections on each reading for each detector before storing this data file.

The Display Software

A new 3-D display software routine (view study) was written to display large data files from the experimental set up. The new routine uses many of the same concepts as our previous VIEWMASTER routine written in 1994. The VIEWMASTER display was only capable of 8 bit (or 256 gray level) display. A selection of contrast range had to be taken from the 16

bit (or 65536 gray level) data that was collected. This limitation was due the limits of memory and speed of the personal computers of that time. the new routine is written for today's new computers and memory. The system uses the full 16 bits of the data which is important because any compromise of the intensity range puts data outside the display range. The display can also provide color as well as the gray level display.

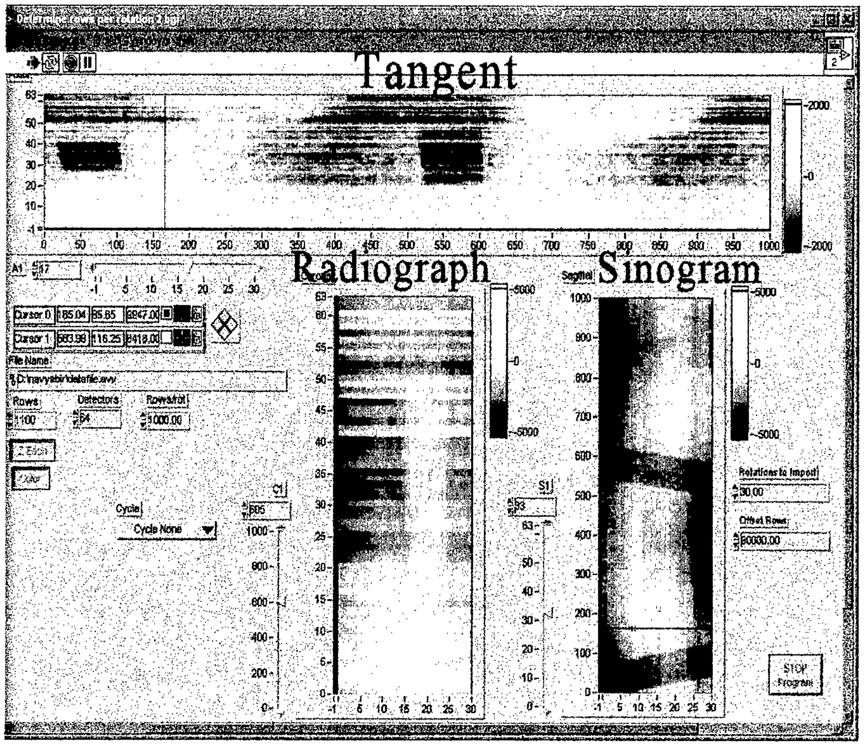

Figure 8: Operator Interface for Display Software.

The display range (level and window) can be set individually for each of the three axis views. A color enhanced display of the three views is shown in Figure 8.

Any one of the three axis views can be cycled through to view the entire set in reasonable time.

A new sorted file of the sinogram data (detector data) can be written. We already have a very powerful data display software routine (ThruVU) written for our pipe scanning system where this sinogram data can be displayed to see very small changes.

The 5" CDI Projectile Phantom Experiments

For tangential data collection, a steel patch (2" x 2" area, 0.035" thick) and a steel wire (0.035" diameter) were attached to the outside surface of one of the 5" CDI projectiles as quality indicators. Later, 0.024" and 0.050" thick MIL STD steel penetrameters were also attached to the surface of the projectile to serve as standard quality indicators.

TANGENTIAL SCANNING. The 5" CDI projectile with the patch and wire was placed vertically on the rotary motion stage of the system. For data collection, the projectile was continuously rotated while translating through the x-ray beam. During most of the data collections, the rotation rate was about 10 seconds per rotation. The translation rate was set at 4 minutes per inch. Hence, it took about 20-25 minutes to collect the data through one projectile. The data collection rate would be significantly faster with higher energy like 450 kV x-ray source.

Over a period of two months, several tangential data sets were collected for the 5" projectile using this experimental set up. We used our x-ray system only at < 280 kV energy because it was showing signs of high voltage arcing above 280 kV voltage.

RESULTS. Figure 8 shows the data from the 5" projectile with 0.035" patch and 0.035" wire using the View Study 3-D display software routine. In this figure all three views of the data are displayed to show features in the projectile surface.

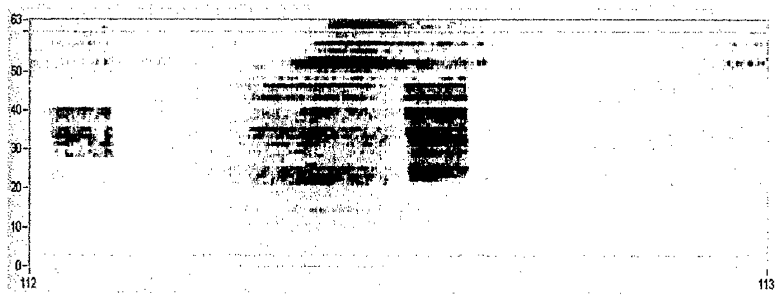

Figure 9: Tangential Data from 5" CDI projectile.

Figure 9 shows the Tangential view of the data, showing the presence of the 0.035" thick patch and 0.035" diameter wire on the surface of the projectile using the ThruVU software. In this view each feature is viewed twice, once when it is near the x-ray tube and second time when it is near the detector. We can easily see the presence of the patch two times in this image. If looked at carefully, we find a faint red vertical line near the right side of the patch images. In the left side image of the patch, it is on the top of the patch itself. In the right side image of the patch, it is slightly right of the patch.

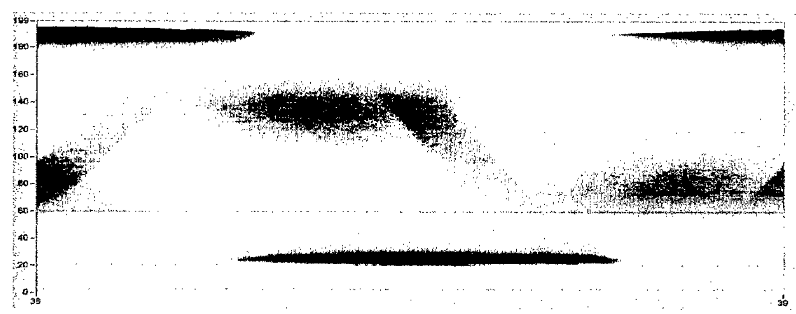

Figure 10: Sinogram Data from 5" CDI projectile.

Figure 10 shows the sinogram view of the data through detector number 31, showing a very prominent sine wave due to the patch at the surface of the projectile. Again, the hint of a sine wave due to the 0.035" diameter wire is also seen in this detector data. The sine wave due to the wire is almost out of phase from the patch sine wave (because the wire is mounted on the opposite side of the patch). In the left side of this sinogram image a thin sine wave due the wire is very clearly seen in the data .

The average energy of the x-ray beam for a 280 kVp x-ray system is approximately 15 keV and, at this energy, the linear attenuation coefficient for iron is about 1.53 cm^{-1}. Hence, only about a 2 x 10^{-6} fraction of the x-ray intensity can reach the detector after passing through the 3.4" path in the CDI projectile. Being able to see the 0.035" thick patch as well as 0.035" diameter wire in this data set shows the phenomenal capabilities of the tangential data collection technique and the 64-channel detector array design.

Figure 11 and figure 12 show the 3-dimensional data from the 5" projectile with the 2.0, 0.050" thick MIL STD penetrameters and the 0.035" thick patch and wire using the View Study 3-D display software routine. Figure 11 shows both the tangential image and a line profile of the same data.

The line profile is the horizontal line that runs through the penetrameters and the patch. The signal levels of the data points along this line are displayed as a graph in the lower half of the figure 11. The profile clearly shows the signal reduction due to the patch and the

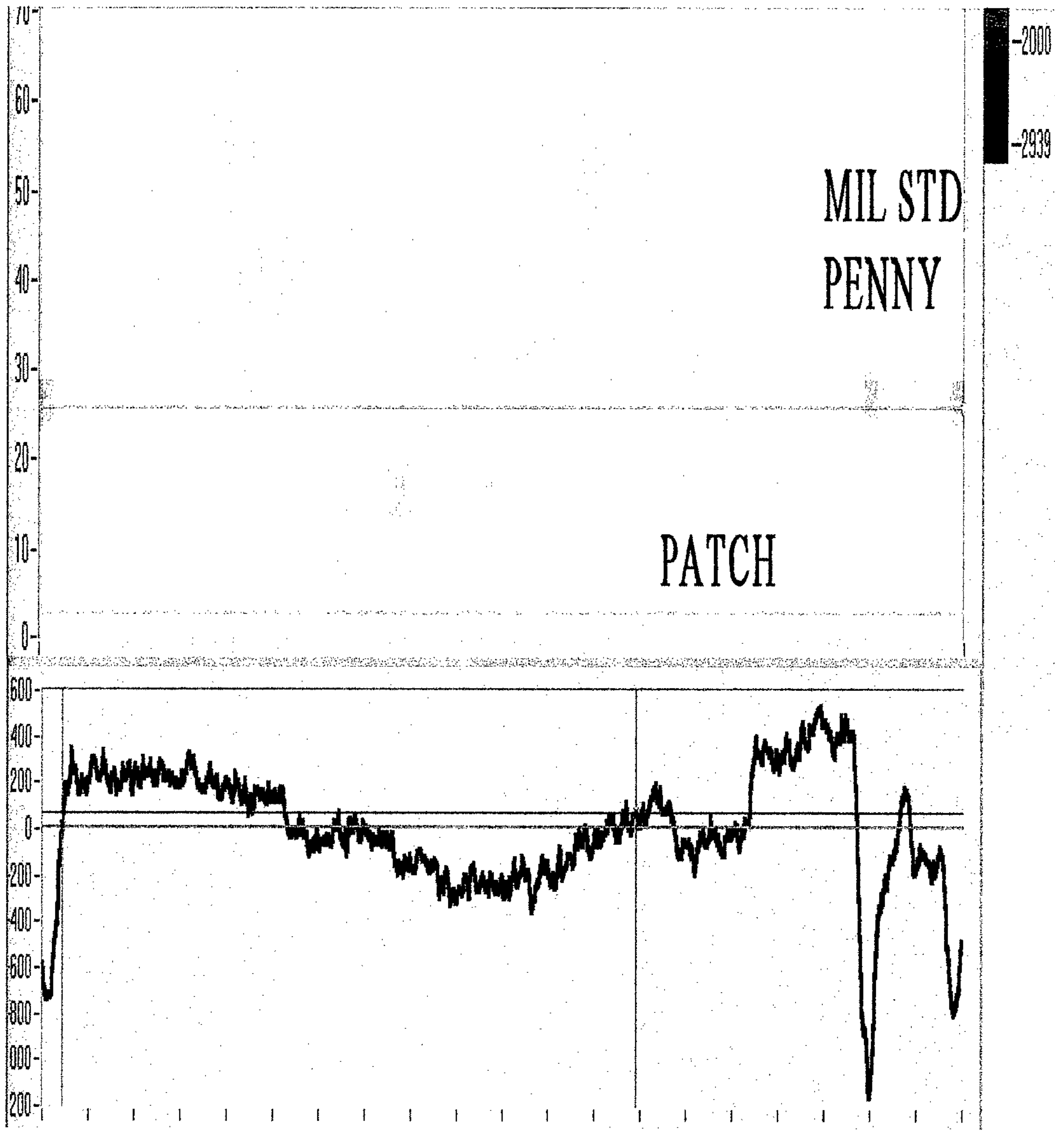

Figure 11: Radiograph View and Line Profile of 5" CDI Projectile.

penetrameters. The signal increase for the 4T and 2T holes in the penetrameters are also visible.

Figure 12 is another data set of this projectile collected with (from left to right) an 0.024" penetrameter, the 0.035" patch, the 0.035" wire, and an 0.050" penetrameter. This data set was processed with offset and gain corrections. The image in figure 12 shows the tangential data through the center of the projectile which is 3.34" thick. The vertical dark line through and above the patch is the wire and the light areas on either side of the wire are due to porosity. The image clearly shows the presence of porosity in this projectile. The patch and the two penetrameters are easily seen. The 2T and the 4T holes in the 0.050" penetrameter can be seen. The 4T hole in the 0.024" penetrameter could be seen in the computer display but due to limited resolution of the printer does not show on the printed page. These results have also been achieved with a 280 kVp x-ray source.

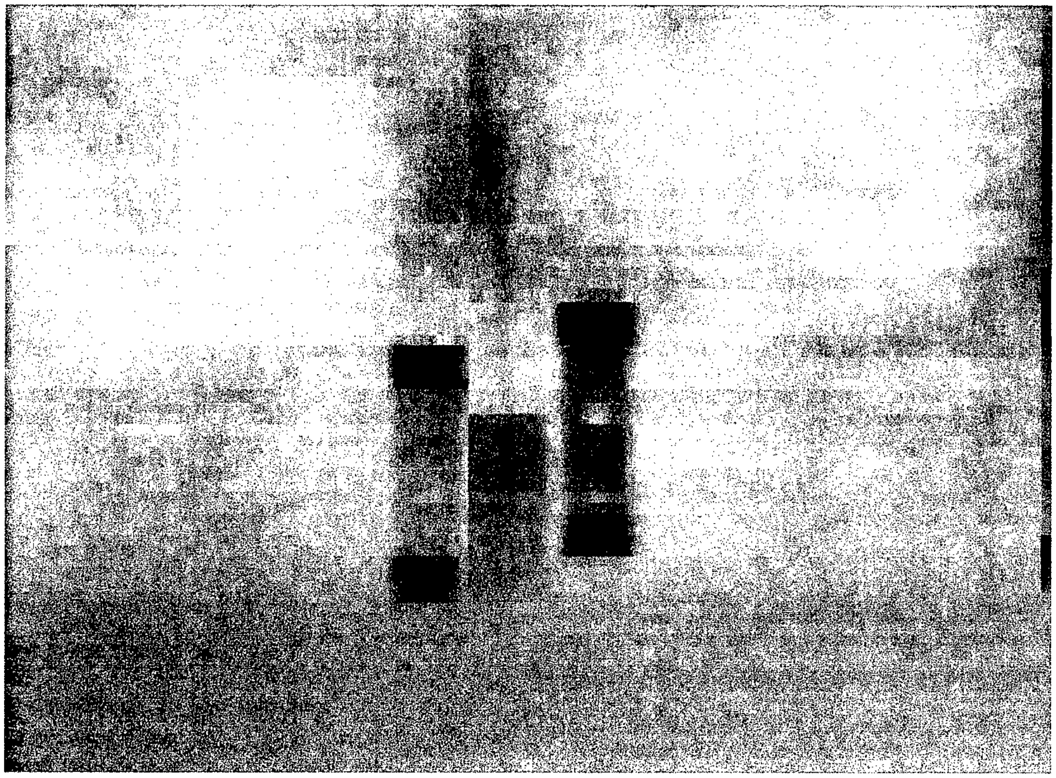

Figure 12: Scan of 5" CDI Projectile with Penetrameters, Patch and Wire.

5. Preliminary Design of a Phase II Prototype RTR System

We propose the following preliminary design for an x-ray tangential scanner system for CDI castings. This recommendation is based on several years of scanning experience of CDI castings, on the experiments done for this phase I work, and on our experience with tangential scanning for rocket motors for NSWC. We will propose to design and build a portion of such system (depending upon the funding level) during phase II.

General Concept and Subsystem Description

The major components of the proposed x--ray radiography system for CDI inspection are:

- A 450 kV high frequency constant potential x-ray generation system,
- One or two linear arrays of solid state x-ray detectors with high speed data acquisition system,
- A computer controlled three (X, Y and Z) axis linear motion system,
- A computer controlled one (Θ) axis rotary motion system,
- A computer based high speed 16 bit analog-to-digital convertor system,
- A high speed Pentium based PC computer system with high resolution display,
- Windows 95 or NT based x-ray data collection software,
- Windows 95 or NT based data correction and analysis software.

A mechanical gantry will house the linear and the rotary motion stages. The x-ray tube and the detector arrays will be mounted on a rigid C-arm structure. A set of tungsten collimators on the x-ray tube and the detector arrays will form a fan shaped beam of x-rays. The CDI casting will be located somewhere in the middle of the x-ray tube and the detector arrays for inspection.

Under the computer control, the linear motion stages will place the CDI casting at the edge of the x-ray beam prior to actual x-ray scanning. During the actual scanning of the casting, the linear and rotary motion stages will rotate the CDI casting and traverse it through the x-ray beam. This will allow the detector system to measure the transmitted x-ray intensity through the casting in all possible directions. During the actual scan of the casting, the solid state detector array and the data acquisition system will measure, digitize and store the x-ray intensity data. The PC based computer system will control the motions and store the collected data during the entire scanning process.

During or after the entire scan through a CDI casting has been completed, the computer system will make necessary correction to the data for individual detector offsets and gains. This is to eliminate the differences in response of individual detectors. This process will:

- Subtract the offset values for each individual detector,
- Multiply the amplification (gain) values for each individual detector,
- Correct for any variations of individual detector response for beam hardness,
- Correct for any x-ray intensity variations in different directions of the beam.

After these corrections, one or more analysis software routines will be applied for flaw detection. The flaw detection software will highlight the area of concern and provide qualitative and quantitative indication of the type and magnitude of the detected flaw in the CDI casting.

For production applications, the individual CDI casting can be removed from the scanning gantry immediately after the x-ray system has collected its data. The x-ray scanning gantry will be ready to collect data for another casting immediately. The data correction and data analysis of the already scanned castings can be carried out by another computer system dedicated for only that task. In this way, the x-ray scanning system will not have to wait for the completion of data analysis before scanning another casting.

X-ray System

Eventually, the NSWC is interested in inspecting very large CDI castings of bomb bodies weighing up to 1000 lbs. We already know that the combination of iron's density ($\rho = 7.86$ gm/cm^3) and its atomic number ($Z = 26$) make the steel a highly x-ray absorbent material. The following table shows the absorption cross sections for steel at a few representative x-ray energies for monoenergetic x-rays.

From the table, it is clear that monoenergetic x-rays of energy < 200 KeV almost do not penetrate through thick steel objects ($\geq$ 3" thickness). Even for 200 KeV energy x-rays, the transmission is only 0.017 %. In an x-ray tube, the x-rays are generated in a Bremsstrahlung process and provide a continuum energy spectra. A 320 kV x-ray generating system will hardly produce an average energy of 150 KeV. Though after passing through several inches of steel, the resulting x-ray beam energy reaches high values, because most of the low energy radiation is already absorbed in the first layers of the metal.

X-ray Energy (KeV)	Mass Atten. cross section (cm^2/gm)	Linear Atten. cross section (cm^{-1})	Transmission through 3" of steel	Transmission through 6" of steel
50	1.911	15.02	0.000 000%	0.000 000%
100	0.3643	2.86	0.000 000%	0.000 000%
150	0.1946	1.53	0.000 009%	0.000 000%
200	0.1452	1.14	0.016 717%	0.000 003%
225	0.1340	1.05	0.033 513%	0.000 011%
300	0.1095	0.86	0.142 555%	0.000 203%
400	0.09372	0.74	0.355 713%	0.001 265%
500	0.08389	0.66	0.654 404%	0.004 282%

A 450 kV x-ray system is expected to produce an average energy of about 225 KeV. Of course, the average energy of the x-ray beam increases as it passes through the materials. As the x-ray beam passes through more material, more and more low energy x-rays are absorbed and the average energy of the beam increases. From the discussions, we understand that as much as a 3" wall thickness may be present in some of the CDI castings. For tangential scanning, a 3" wall thickness means that the x-ray beam may have to pass through up to 6" of steel (giving a transmission of 11×10^{-6}). We estimate that a high frequency constant potential 450 kV should be the minimum x-ray system one should even consider for CDI castings. Our experience in phase I has proven that with 150 kV x-ray energy, it is almost possible to see through 1.66" of steel and with 300 kV x-ray beam through 4" of steel.

X-ray Detector System

The first detector system will be used for outside x-ray intensity measurements to make double wall measurements. This detector system will be physically too large to insert through the hollow cavity of the bomb body. Hence, this detector system will be used in a tangential scanning mode to measure x-ray intensity data through both walls of the bomb body. This detector array will be located outside the CDI casting. The CDI casting will rotate and traverse over this detector system for x-ray intensity measurements through both walls of the casting.

There will be 128 or 192 detector elements, organized in 2 or 3 modules of 64 channels. Each module will be 8.32" wide, and will have 64 scintillator crystals mounted on an array of 64 silicon photo diodes, together with 64 channels of analog circuits (amplifiers plus integrators), and eight 8:1 multiplexers followed by a line driver circuit.

Each 64-channel module will also include logic circuits to drive multiplexers and integrators synchronized to an external trigger pulse. This will eliminate the need for an external DAS (Data Acquisition System), all components of a DAS system will be incorporated within the detector array itself. The entire detector array will be housed inside an aluminum extrusion and environmentally sealed for long life. The detector array will also contain at least 1/8" thick lead shielding for some scatter rejection. Further radiation shielding and collimation will be added external to the housing.

The scintillator crystals will be cadmium tungstate ($CdWO_4$). The $CdWO_4$ scintillator crystals would be 3 mm wide (located at a pitch 3.33 mm) in the resolution direction. The scintillator would be 9 mm long in the slice direction and 6 mm deep in the x-ray beam direction. With 6 mm depth, the $CdWO_4$ scintillator crystal will detect over 70% of the photons from the 450 kV x-ray source, even after the x-rays have been hardened by passing through 3" of steel.

Cadmium tungstate is chosen for its high x-ray stopping power and because it is substantially freer from afterglow compared to other materials. In addition, its light output is an excellent spectral match with the silicon photo diode response. Finally, it is a long-life stable material as compared to cesium iodide, or to highly hygroscopic sodium iodide. Unlike these, $CdWO_4$ performance is not degraded by radiation exposure, heat, or ultraviolet light.

The detector system will use a parallel plate post object collimator system located just above the detector array. The parallel plate post object collimator will be made out of lead or tungsten and would be 0.5" thick and would have an adjustable opening. The typical opening of the tungsten collimator blades is expected to be 0.125". At an opening of 0.125", the scatter rejection factor from post object collimator would be about 10 to 1 in x-ray beam-width direction.

The actual $CdWO_4$ scintillator crystal detectors will be 9 mm long. But as discussed before, they will be limited to 0.125" by the collimator in a typical application. In some applications (through deeper steel thickness) the x-ray intensity may be too small and may require wider opening of the collimator to increase the detected x-ray signal intensity. When and if we need longer detector length for such applications, the width of the collimator can be adjusted.

Reference Detector System

A reference detector can be used to measure the intensity of the x-ray tube at all times. If the x-ray tube intensity drifts or varies in time, then a reference detector can provide a method to correct for these variations.

If needed, a single reference detector (of design similar to one channel of the 64-channel detector) will be incorporated near the x-ray tube and would constantly monitor the intensity of the x-ray source beam. This reference detector output would be used to correct all individual detector readings and thus eliminating the variations in the detector data due to time variations in the x-ray source intensity. This reference detector will be incorporated in the system only if the stability of the x-ray output requires it.

Analog-to-Digital Convertor (ADC) Board

The final multiplexed signal from the entire detector array would be digitized by one true 16 bit analog-to-digital (A/D) conversion board. Thus one single A/D converter will receive the multiplexed analog data stream from all detectors, and will convert it into a single true 16 bit parallel digital data stream using a true 16 bit fast ADC. The analog board containing the 16 bit ADC will be located inside the PC computer system.

We propose to use the PC/AT based ADC board manufactured by National Instrument model number AT-MIO-16X. This is a true 16 bit analog-to-digital convertor board with a conversion rate of 100,000 conversions per second. Omega is currently using such a ADC board in other systems with good results.

Hence, the entire linear detector array (consisting of 128 or 192 channels) can be digitized at a rate of 100,000 data points per second or 1.6 msec per data line. In actual practice, the detector array will be digitized at about 10 msec per data line. Every detector would integrate the x-ray signal for the entire 10 msec period.

Second Detector System

A second detector system will be designed for single wall measurements through the CDI castings. This detector system will be identical to the first detector system in concept but will be smaller and narrower in physical size. This detector system will be capable of being inserted inside the hollow cavity of the bomb body for single wall measurements.

There will be 64 detector elements, organized in 8 modules. Each module will be only 1" wide and 1" long and will have 8 scintillators on 8 silicon photo diodes, together with 8 channels of preamplifiers and integrators. Each scintillators will be cadmium tungstate and measure 3 mm x 3 mm wide. The scintillators will be 6 mm deep in the x-ray beam direction to provide decent efficiency for 450 kV x-ray beam. This will make a fairly narrow detector array so that it can be inserted through the hollow cavity in the typical CDI casting for single wall measurements.

This second detector system will have its own external data acquisition system (DAS). The same ADC board and computer system can be used for both detector systems.

Mechanical Gantry

The mechanical gantry will be made of two components.

- *The CDI casting platform* which will incorporate all of the motions required for scanning the casting. For data collection during x-ray scanning, the x-ray beam will remain stationary and the CDI casting will make all the motions through the stationary x-ray beam.
- *The source-detector C-arm* which will rigidly hold the x-ray tube and the detector arrays around the CDI casting. The x-ray tube will be mounted on one end of the C-arm and the detector arrays on the other. The fan beam collimator at the x-ray tube and the post object collimator at the detector array will define the x-ray beam of the system. The detector system and the x-ray tube will be precisely aligned with each other and form the stationary x-ray beam for scanning the CDI castings.

THE CDI CASTING PLATFORM. The casting platform will have four independently controllable motion stages designed to accommodate bombs weighing up to 1000 lbs. Of these four stages, three will be linear motion stages. The linear stages will provide motions in X, Y and Z axis *i.e,.* in the horizontal and vertical planes. The fourth motion stage will provide the rotary motion. The figure 13 shows a concept of the platform with rotational axis in the vertical direction.

The axis of rotation can be in the horizontal or vertical plane. At present, it is not clear whether horizontal or vertical axis of rotation is superior for this application. The horizontal axis provides greater stability to the bomb body during the scanning sequence. For the horizontal axis, the bomb has to be supported and chucked from both ends. This can cause a movement of the axis of rotation and thus an error in the interpretation of the collected data. On the other hand, the vertical axis provides a fixed axis of rotation and better control over the rotation speed. But, the bomb bodies are long and narrow which can make them

unstable in the vertical direction. For a vertical axis of rotation also, we would have to chuck the bomb body from both bottom and top.

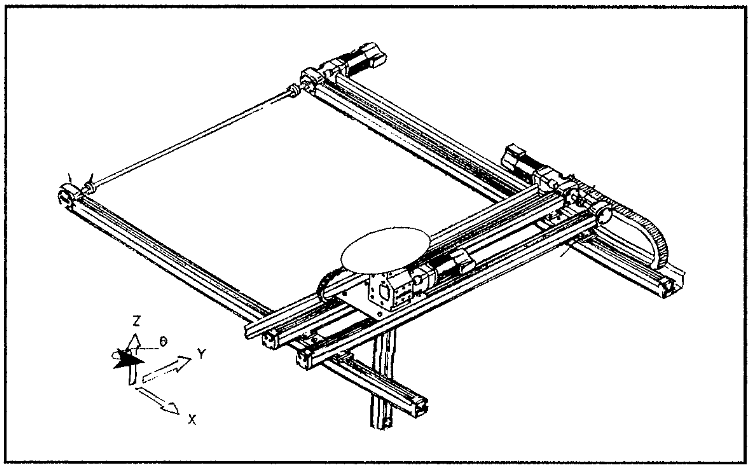

Figure 13: CDI Casting Platform Concept

For maximum flexibility, the gantry system will incorporate 4' x 4' motion along the X and Y axis in the horizontal plane. The Z axis motion in the vertical direction will be limited to about 2' only. During the actual tangential scanning process, we require only one linear motion and one rotary motion. One more linear motion is required to align the CDI casting with the x-ray beam. We are proposing an additional linear motion (total of three linear motions) to provide flexibility in the prototype system. The rotary (Θ) motion will provide 360^0 continuous rotation of the bomb body. As discussed before, the rotary axis may be either in the horizontal or vertical plane.

THE SOURCE-DETECTOR C-ARM. From steel weldments or aluminum extruded components, a structure will be fabricated to hold the x-ray tube and the detector array around the CDI casting on the platform. The x-ray tube will be mounted on one end of the C-arm and the detector array on the other end. The x-ray tube will incorporate its collimator and the detector array will have its post object collimator. The x-ray tube, detector array and the pair of collimators will form the fan shaped x-ray beam to be used for scanning the CDI casting. The detector system collimator and the x-ray tube collimator will be precisely aligned with each other and form the stationary x-ray beam for scanning of CDI castings.

If the axis of rotation of the CDI casting on the platform is designed to be in the vertical direction, then the detector array will also be mounted in the vertical direction. The fan shaped x-ray beam also will be in the vertical plane and covering the axis of rotation.

On the other hand, if the axis of rotation of the CDI casting on the platform is designed to be in the horizontal direction, then the detector array will also be mounted in the horizontal direction. The fan shaped x-ray beam will still be in the vertical plane and covering the axis of rotation.

The source-detector C-arm will remain stationary and only the CDI casting will be moved and rotated to scan the casting. Hence, the detector array will always remain precisely aligned to the x-ray beam.

The Computer System

We propose to use a PC compatible computer system with maximum computing speed available at the time of purchase. The computer for the CDI scanner will most probably be a system based on Pentium or higher order chip set. The system will include 64 Mbytes or more system memory, several Gbytes of hard drive space and excellent graphics display

capability. The system will also include network capability to load the software and data back and forth between our other software development computer systems.

Probably, the ADC board and the motion control boards will also be included inside the same computer system. If another computer is used for motion control then it will be controlled by the main computer through network connection.

The CDI scanner computer system will control the gantry motions, collect the data from the detector systems and process the data for corrections and data analysis for flaw detection. The computer system will also be used for data presentations in the form of images and text files.

X-ray Data Collection and Gantry Motion Control Software

Omega will write custom software to control and collect data from the detector system. The data collection software will be written using the National Instrument's LabVIEW platform under Windows 95 or Windows NT. The LabVIEW is a Windows based data collection and mathematical analysis software package. The LabVIEW package already includes the high level software drivers for the proposed ADC board.

Several commercially available motion control systems also use LabVIEW platform. Commercial LabVIEW based software routines are already available for some of these controller boards. We propose to use a commercially available motion control system with already available software drivers under LabVIEW environment. Hence the data collection and gantry motion control software will be simple and Windows based.

Data Correction and Analysis Software

All custom data correction and analysis software routines will be written using the LabVIEW's mathematical and analysis tools. Omega has extensive experience with the LabVIEW library and has written many similar successful tools for data collection as well as analysis. Future CDI scanner software routines will use many of the building blocks already in place at Omega. Some of these building blocks were generated during the phase I of this SBIR contract. While others have been developed under our internal R&D effort.

These software routines will include at least following modules:

- Gantry control and data collection routines with operator selected parameters for various size and shapes bombs as needed,
- Data correction routines to eliminate differences due to detector offsets and gains and x-ray beam hardness.
- Data processing routines to identify abnormalities and defects in the scanned bomb body. The data processing will include tools like averaging of the data, mask subtraction, second or higher order fit to the data, differentiation of the data, smoothing of the data and other types of convolution of the data.

6. Three-dimensional Data Display Software

Omega has a very successful custom image display and analysis routine known as VIEWMASTER. As discussed before, during the phase I of this contract, Omega has improved upon this 3-D software routine (new routine is known as View Study) by including several new features. The View Study program:

- Uses 16 bit data,
- The display range (level and window) can be set individually for each of the three axis views,
- Any one of the three axis views can be cycled through to view the entire data set in reasonable time,
- A new sorted file of the sinogram data (detector data) can be written. We already have a very powerful data display software routine (ThruVU) written for our pipe scanning system where this sinogram data can be displayed to see very small changes.

Except for above improvements, the ViewMaster program and View Study program are almost identical. Following is a description of our ViewMaster program.

This routine was extensively used with the tangential CT scanner system supplied to NSWC under the SBIR contract. The ViewMaster also operates under the Windows environment. In addition to the image display, the CDI casting scanner system will also include other forms of data presentation like graphing and text files.

Our software package displays the entire volume of collected data from the scanner in three different modes. All three modes of data display are simultaneously available in real-time. The actual data collection concept and three modes of display are shown in figure 14.

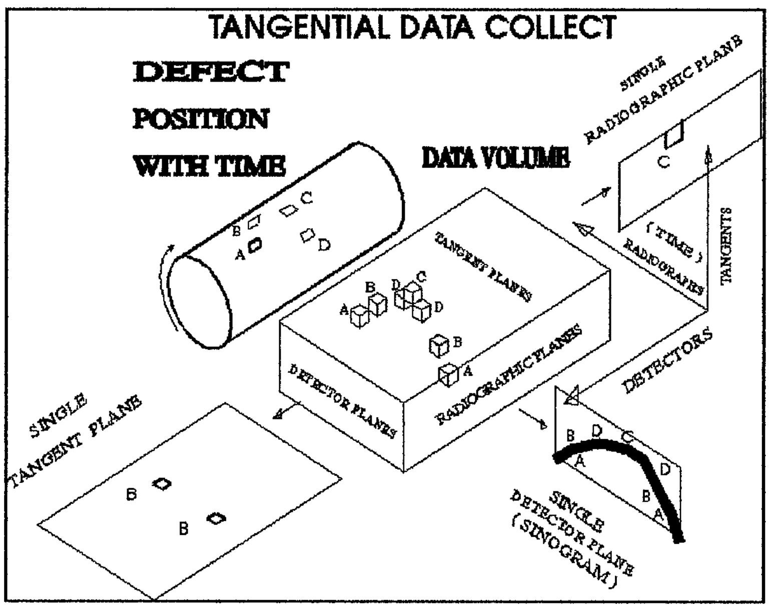

Figure 14: Concept of Data Views.

In one mode the data is displayed in the form of tangential views at various radius of the object. This data display is equivalent to unfolding a roll of paper towel one layer at time. This mode displays the unrolled view of each layer at a time. Any and all individual layers of the object can be viewed in this mode. The data display in this mode is very sensitive to the thin laminar defects.

The second mode displays the data for each detector of the detector array. The individual detector data is a sinogram for an individual slice of the object. The individual sinogram from each detector is a complete set of raw data which can be used to reconstruct individual CT slices. Thus the sinograms from all detectors together can be used to reconstruct all CT slices of the entire object *i.e.*, volume CT image of the object. The entire data set from each detector is contained in one layer of the detector data set. If the scanner has 128 (192) detectors, there will be 128 (192) layers of sinogram data available to the operator.

The third mode displays the data in the form of digital x-ray radiographs of the object. The total data set is organized in layers where each layer contains one radiographic image of the object. The successive layers in this mode are radiographs after a slight rotation of the object. This mode is similar to radiographic images of a rotating object in a real-time radiography (RTR) system. The operator can roam through various layers of the data set and actually view successive radiographic images as the object rotates. In a typical x-ray data set, there may be several hundred to several thousand such digital radiographs available. For comparison, in a typical digital radiography system, only one or two such digital x-ray radiographs are collected for any object.

A TYPICAL EXAMPLE OF OUR 3-DIMENSIONAL DATA DISPLAY SOFTWARE - The NSWC-Dahlgren Rocket Motors Phantom

A tangential CT scanning system was designed for inspecting small and large Rocket Motors but the same technology also has a great potential for CDI castings. The data collected from a rocket motor phantom is displayed in the adjacent figure 15 using our VIEWMASTER image display software. This phantom is made of a 4" diameter cylindrical pipe filled with simulated rocket fuel. Another 1.5" diameter tube is located in the middle of this phantom. This 1.5" diameter tube extends from one end to only the middle of the phantom along its length. This particular phantom contains two unbond type defects between the simulated rocket fuel and the external 4" wall. It also contains two additional unbond types defects between the simulated fuel and internal 1.5" wall. It also contains two notches cut out at the inside of the internal 1.5" wall along its full length.

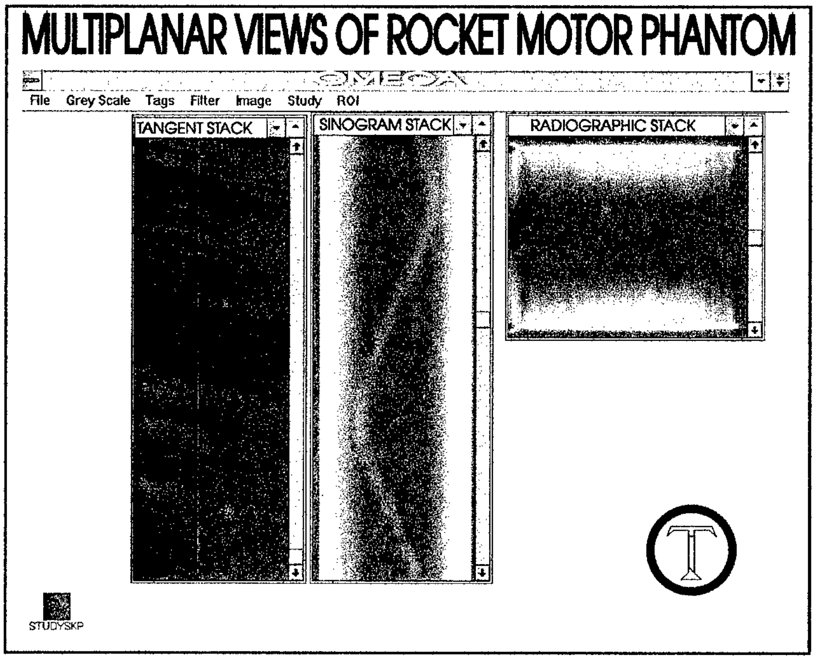

Figure 15: VIEWMASTER Display Software.

In the figure 15, all three views *i.e.*, tangential, detector sinogram and radiographic views are shown in that order for the NSWC rocket motor phantom. The left side image of this figure shows the tangential view. In this view we see several bright sections in the image indicating larger x-ray signal or loss of material due to unbond defects. Due to 360° scanning, each defect shows up twice in the tangential data, once when the defect is towards the x-ray tube and second time when it is towards the detector side. We also see indication of two notches which extend from one end of the image to the middle of the image.

The middle image of this figure shows the detector sinogram view. In this view we see two faint sine waves in the middle which extend only to the inside wall of the internal 1.5" tube. This is a signal from the two notches towards the inside of the internal tube. These two sine waves are also out of phase from each other, indicating that these notches are 180°. from each other. We also see a fairly bright sine wave which extends to the outside wall of the internal tube, indicating a unbond defect on the outside of the internal 1.5" tube. We also see a faint indication of another sine wave which extends to the outside wall, indicating a unbond at the outer wall. Since the defects are located at different locations along the length of the phantom, all defects do not show up in this particular detector. Other unbond defects are indicated in other detector sinograms.

The right side image of the figure shows the radiographic view of the phantom. In this image we see the presence of the two notches and several unbond features. When we view the successive layers of the radiographic view images, we view the rotation of the notches and unbond features. Again, the notches extend only to the middle of the phantom along its length. Two of the unbond features travel to the outside tube while the other two travel to the inside tube of the phantom. Thus each of these three image views contains sufficient information to pinpoint exactly, the extent and location of a defect. The three views together make it significantly easier to find the location and amplitude of the problem.

7. Conclusions

During phase I, several technical tasks were carried out to collect two sets of data.

(1) The data was collected with the 150 kV x-ray system and a single channel x-ray detector from a 3" diameter simulated steel phantom (with a 0.028" hole).

(2) The data was collected with a 300 kV x-ray system and a 64-channel detector array from a 5" CDI projectile (with a 0.035" thick patch and a 0.035" diameter wire).

Both data sets clearly indicate that the proposed design of a tangential technique scanner can detect and exactly locate small flaws and features in the CDI castings. The data also shows that, by using this approach, the results can be obtained at significantly lower energy than is generally used – this mean lower system and facilities costs.

Some of the software and hardware already developed can be used to achieved the goals of this project without any significant technical risks. Ultimately, such a tangential scanning system can learn and automatically detect most flaws and defects in navy's large and small CDI castings.

8. Future Recommendation

We suggest that a prototype tangential scanner system be designed and fabricated during the phase II period to evaluate the performance of such a system for CDI castings. To be within the funding constraints of the phase II, we suggest that the phase II prototype mechanical gantry be limited to scanning lighter weight (up to 200 lbs) CDI castings only, and that one of the motion stages of the gantry also be eliminated. This would limit the phase II prototype scanner to scanning only 200 lbs castings. In all other respects, the prototype scanner would have all the performance of the final scanning system.

This will simplify and lower the cost of the gantry design. Later, the gantry designs can be updated for production application during phase III. Some of the automated flaw detection software should also be eliminated from phase II and should be achieved during phase III of this project.

On the assumption that the phase II prototype is successful, we would recommend to fabricate a complete tangential scanning system during phase III, to be delivered to NSWC or Lufkin Industries, the CDI casting manufacturer. The phase III system can be nothing more than updating the already built phase II prototype. Most of the actual components of the phase II prototype system can be used in the phase II system. This will reduce the phase III system to a minimal level.